

MCNP6 Study of Fragmentation Products from $^{112}\text{Sn} + ^{112}\text{Sn}$ and $^{124}\text{Sn} + ^{124}\text{Sn}$ at 1 GeV/nucleon

S.G. Mashnik^{1,*} and A.J. Sierk¹

¹*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

(Dated: March 20, 2013)

Isotope production cross sections from $^{112}\text{Sn} + ^{112}\text{Sn}$ and $^{124}\text{Sn} + ^{124}\text{Sn}$ reactions at 1 GeV/nucleon, which were measured recently at GSI using the heavy-ion accelerator SIS18 and the Fragment Separator (FRS), have been analyzed with the latest Los Alamos Monte-Carlo transport code MCNP6 using the LAQGSM03.03 event generator. MCNP6 reproduces reasonably well all the measured cross sections. Comparison of the MCNP6 results with the measured data and with calculations by a modification of the Los Alamos version of the Quark-Gluon String Model allowing for multifragmentation processes in the framework of the Statistical Multifragmentation Model (SMM) by Botvina and coauthors, as realized in the code LAQGSM03.S1, does not suggest unambiguous evidence of a multifragmentation signature.

I. INTRODUCTION

MCNP6 [1] is used in various applications involving reactions induced by neutrons and other particles, but also may be applied to heavy-ion collisions at relativistic energies. The Los Alamos version of the Quark-Gluon String Model (LAQGSM), implemented in the code LAQGSM03.03 [2], is the main “workhorse” (event generator) used by MCNP6 to describe relativistic heavy-ion interactions. It is critical that it be able to describe such reactions as well as possible; therefore, it is extensively validated and verified against available experimental data and calculations by other models (see, e.g., [3] and references therein). So far, for relativistic heavy-ion collisions, MCNP6 has been compared mostly with different particle spectra measured from various reactions [3] and much less with data on isotope-production yields. To remedy this lack, we test MCNP6 and the LAQGSM03.03 [2] and LAQGSM03.S1 [7] versions of LAQGSM against the recent GSI measurements of fragmentation products in the reactions $^{112}\text{Sn} + ^{112}\text{Sn}$ and $^{124}\text{Sn} + ^{124}\text{Sn}$ at 1 GeV/A [4]. These data are interesting because we may use them to study the influence of the isotopic composition of the projectile and target on the kinematical properties of projectile residues, which may help improve understanding of the physics of nuclear-fragmentation reactions.

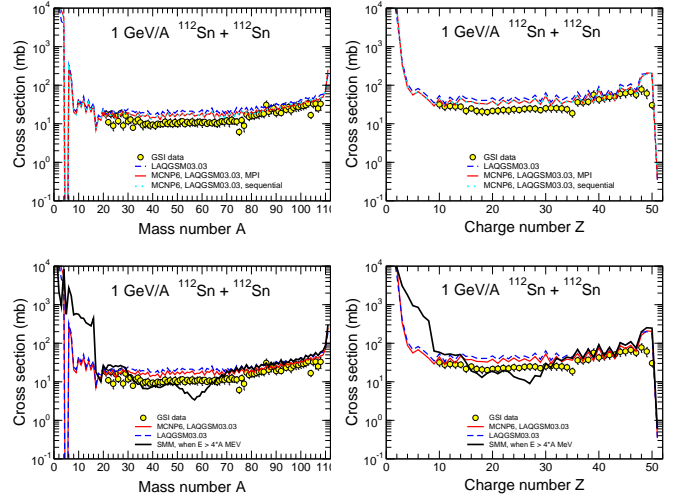


FIG. 1. Experimental [4] mass and charge distributions of products from 1 GeV/A $^{112}\text{Sn} + ^{112}\text{Sn}$ (yellow points) compared with results by LAQGSM03.03 used as a stand-alone code (blue dashed lines) and with MCNP6 calculations in parallel (MPI, red solid lines) and sequential (green dashed lines) modes using the LAQGSM03.03 event generator are in the upper plots, while results from the LAQGSM03.S1 version of LAQGSM, which takes into account multifragmentation processes with SMM [5], for nuclei with excitation energies E above $4 \times A$ MeV (black solid lines), are in the lower plots.

II. RESULTS

As part of the MCNP6 Verification and Validation (V&V) process, we calculate both $^{112}\text{Sn} + ^{112}\text{Sn}$ and $^{124}\text{Sn} + ^{124}\text{Sn}$ reactions using the LAQGSM03.03 event

* Corresponding author, electronic address: mashnik@lanl.gov

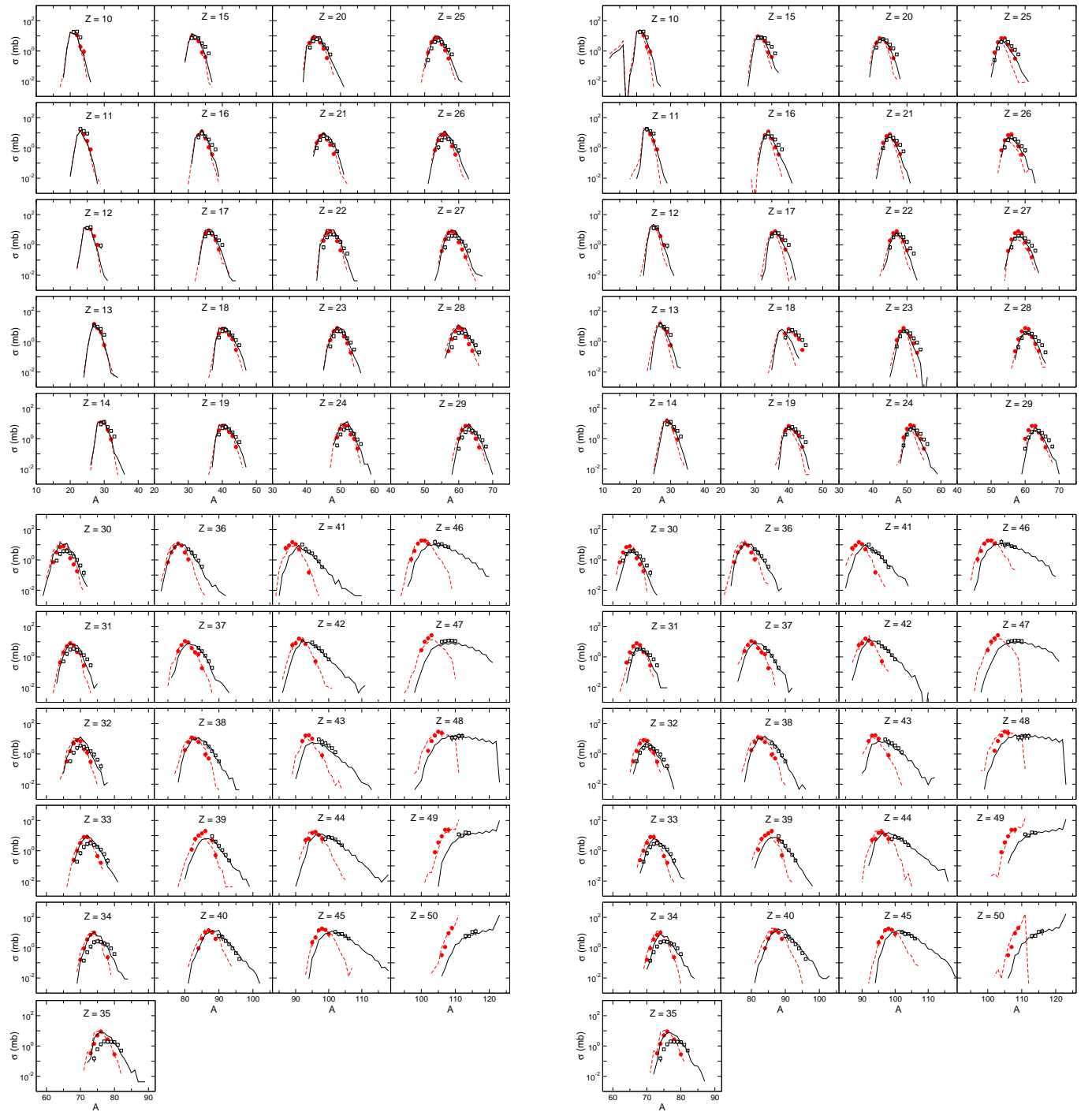


FIG. 2. Isotopic cross sections of all measured fragments [4] in the reactions 1 GeV/A $^{112}\text{Sn}+^{112}\text{Sn}$ (red solid circles) and $^{124}\text{Sn}+^{124}\text{Sn}$ (black open squares) compared with results from LAQGSM03.03 [2] (red dashed and black solid lines, correspondingly) in the left panel and those from LAQGSM03.S1 [7], which accounts for multifragmentation processes with SMM [5] for nuclei with excitation energies $E \geq 4 \times A$ MeV, in the right panel.

generator, both running MCNP6 in a sequential mode and in parallel using MPI. We also calculate both reactions with LAQGSM03.03 used as a stand-alone code, outside MCNP6. As expected, all results obtained with MCNP6 run with MPI coincide with the ones calculated

in a sequential mode. Similarly, all the results obtained with MCNP6 using LAQGSM03.03 are practically the same as the calculations done with LAQGSM03.03 by itself, with only a tiny uniform difference in the absolute values of all cross sections, due to different values for the

total reaction cross-section normalizations used by the two code systems. In principle, there could be other problems with the implementation of LAQGSM into MCNP6, but there are no apparent discrepancies for these particular reactions. Examples of some results from our study for the $^{112}\text{Sn}+^{112}\text{Sn}$ reaction, are presented in the upper plots of Fig. 1.

The LAQGSM03.03 version of LAQGSM, as implemented in MCNP6, does not account for multifragmentation of highly excited nuclei. It models Fermi Break-up of light nuclei with $A < 13$ (see details in [2]), but this is not what one usually means by “multifragmentation” (see, e.g., [5] and references therein). In addition, Fermi Break-up is only used in LAQGSM for nuclei with $A < 13$.

To investigate further the mechanisms of nuclide production in these reactions, we calculate both reactions with a version of LAQGSM, LAQGSM03.S1 [7], which accounts for multifragmentation processes using the Statistical Multifragmentation Model (SMM) of Botvina et al. [5]. One of the most important details in SMM is the condition for the transition between the multifragmentation and vaporization (or evaporation) modes of a reaction, which is determined by the temperature of the excited nucleus, or by its excitation energy, E . It is believed that such a transition should occur at excitation energies E/A from ~ 3 to ~ 5 MeV/nucleon, depending on the concrete type of the reaction (see the recent review by Borderie and Rivet [6] and references therein). We perform calculations with LAQGSM03.S1 for the transition condition defined by E/A equal to 4 MeV/nucleon.

We find that for these reactions the results obtained with LAQGSM03.S1 are close to the values of the product cross-section yields calculated with LAQGSM03.03 or MCNP6. Examples of mass and charge distributions

of products from the $^{112}\text{Sn}+^{112}\text{Sn}$ reaction calculated with LAQGSM03.S1 are compared with similar results by LAQGSM03.03 and by MCNP6 with LAQGSM03.03 in the lower plots of Fig. 1.

A more detailed comparison of results by LAQGSM03.S1 and LAQGSM03.03 in MCNP6 is presented in Fig. 2, where the left panel shows isotopic cross sections of all measured products from both reactions compared with calculations by LAQGSM03.03, while the right panel shows the same data compared with results by LAQGSM03.S1. A careful one-by-one comparison of the plots from the left panel with the ones from the right panel does not suggest an unambiguous signature of multifragmentation reactions in this data. We came to a similar conclusion in Ref. [8] while analyzing other comparable heavy-ion reactions. Mancusi et al. also made a similar conclusion from a study of 1-GeV proton-nucleus reactions [9].

III. CONCLUSIONS

The recent GSI measurements $^{112}\text{Sn} + ^{112}\text{Sn}$ and $^{124}\text{Sn} + ^{124}\text{Sn}$ at 1 GeV/nucleon have been analyzed with the Los Alamos transport code MCNP6, using the LAQGSM03.03 event generator. MCNP6 reproduces reasonably well all the measured cross sections. All the MCNP6 results obtained in a sequential run coincide with those obtained using a parallel version. Comparisons of our MCNP6 results with the measured data do not differ by large amounts from those from calculations by a modified LAQGSM allowing for multifragmentation processes in the framework of the Statistical Multifragmentation Model (SMM). Within the constraints of these particular models, there does not seem to be any evidence unambiguously suggesting a multifragmentation signature in these reactions.

-
- [1] T. Goorley et al., NUCL. TECHNOL. **180**, 298 (2012).
 - [2] S.G. Mashnik et al., LANL REPORT LA-UR-08-2931, Los Alamos 2008, arXiv:0805.0751, <http://mcnp.lanl.gov/>.
 - [3] S.G. Mashnik, EUR. PHYS. J. PLUS **126**, 49 (2011).
 - [4] V. Föhr et al., PHYS. REV. C **84**, 054605 (2011).
 - [5] A.S. Botvina et al., NUCL. PHYS. **A475**, 663 (1987); J.P. Bondorf et al., PHYS. REP. **257**, 133 (1995).
 - [6] B. Borderie and M.F. Rivet, PROG. PART. NUCL. PHYS. **61**, 551 (2008).
 - [7] S.G. Mashnik et al., LANL REPORT LA-UR-06-1764, Los Alamos 2006 <http://mcnp.lanl.gov/>.
 - [8] S.G. Mashnik et al., LANL REPORT LA-UR-06-1955, Los Alamos 2006, arXiv:nucl/th-0603046.
 - [9] D. Mancusi et al., PHYS. REV. C **84**, 064615 (2011).